

# **NANO-PATTERNED QUANTUM STRUCTURES FOR INFRARED DETECTION**

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**30 September 2005**

**Final Report**

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**AIR FORCE RESEARCH LABORATORY  
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3550 Aberdeen Ave SE  
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AFRL-VS-PS-TR-2005-1192

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 30/09/2005		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 01/10/2002 to 30/09/2005	
4. TITLE AND SUBTITLE Nano-Patterned Quantum Structures for Infrared Detection				5a. CONTRACT NUMBER F29601-02-C-0267	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 62601F	
6. AUTHOR(S) Daniel C. Tsui				5d. PROJECT NUMBER 4846	
				5e. TASK NUMBER CR	
				5f. WORK UNIT NUMBER A1	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Princeton University Department of Electrical Engineering E-quad, B426 Princeton, NJ 08544				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory Space Vehicles Directorate 3550 Aberdeen Ave., SE Kirtland AFB, NM 87117-5776				10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/VSSS	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-VS-PS-TR-2005-1192	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT  This is the final report of work accomplished under contract #F29601-02-C-0267 from the Air Force Research Laboratory (Kirtland), which was a three-year research project with two focused objectives: (1) To develop voltage tunable two-color superlattice QWIPs and broadband QWIPs, and (2) to fabricate quantum-dot QWIPs using nano-patterning and to investigate their infrared detection characteristics arising from the three-dimensional confinement of electrons in the semiconductor device structure.  The project was funded from October 2002 to July 2004, approximately 2/3 of the originally agreed 3 years. Consequently, part of the second objective was not reached. More specifically, the nano-patterned quantum-dot QWIPs were fabricated, but their infrared detection characteristics were not investigated.					
15. SUBJECT TERMS SPACE VEHICLES, INFRARED, DETECTORS, QUANTUMDOTS, NANOPATTERNED STRUCTURES, QUANTUM GRID IR PHOTODETECTORS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			Dr. Danhong Huang
			SAR	16	19b. TELEPHONE NUMBER (include area code) (505) 846-5788



# **Nano-Patterned Quantum Structures for Infrared Detection**

## **F29601-02-C-0267**

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(Account #: 170-6411)

**September, 8 2005**

### **I. Introduction**

This is the final report of work accomplished under contract #F29601-02-C-0267 from the Air Force Research Laboratory (Kirtland), which was a three year research project with two focused objectives: (1) To develop voltage tunable two-color superlattice QWIP's and broadband QWIP's, and (2) to fabricate quantum-dot QWIP's using nano-patterning and to investigate their infrared detection characteristics arising from the three-dimensional confinement of electrons in the semiconductor device structure.

The project was funded from October 2002 to July 2004, approximately 2/3 of the originally agreed 3 years. Consequently, part of the second objective was not reached. More specifically, the nano-patterned quantum-dot QWIP's were fabricated, but their infrared detection characteristics were not investigated.

### **II. Technical Accomplishments**

#### **a. Two-color QWIP's and broadband QWIP's.**

- a1. We have studied two approaches in achieving voltage tunable two-color detection. In one of the approaches, we adopted a QWIP structure with coupled quantum well pairs as its unit cell. Under a finite bias, the ground state of one of the QWs in the pair is the lowest energy state. The doped electrons reside exclusively in this state, which leads to certain infrared absorption wavelength determined by this QW's parameters. When the bias is reversed, the other QW has the lowest energy state, which causes the transfer of doped electrons into this well. The detection wavelength is thus changed. Under this approach, we have demonstrated the switching of wavelength from 7 to 9  $\mu\text{m}$  when the bias changes from 1 V to -3 V. Fig. 1 shows the spectral response under different bias polarities. By monitoring the strength of responsivities of the two wavelengths, we are able to deduce the change of electron occupation in these two wells as a function of temperature. Fig. 2 shows the changes.

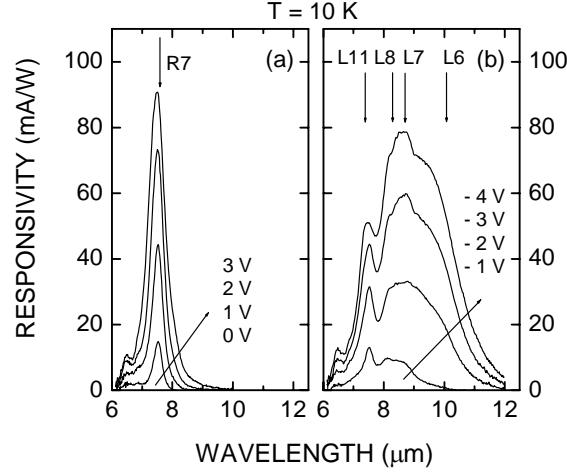


Fig. 1 Spectral response under different bias.

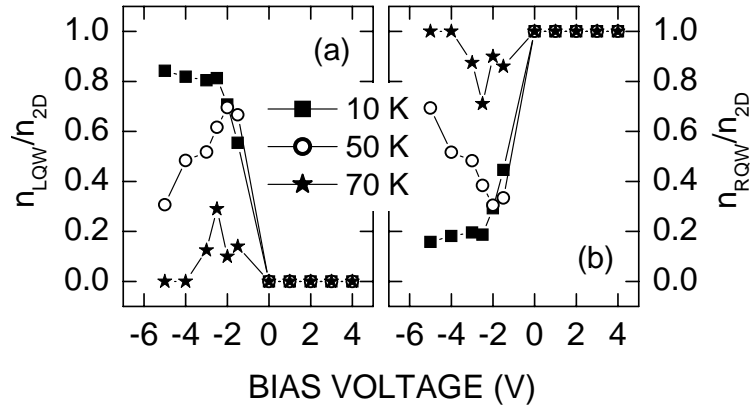


Fig. 2 The change of electron density in the left and right QWs as a function of bias and temperature

- a2. The second approach in voltage tunable detection has been reported in our previous progress report. We will describe it briefly here. The approach uses superlattice pairs as unit cells in the QWIP structure. In each SL pair, there is a barrier blocking the electrical conduction of the ground minibands. In this structure, we utilize the fact that only one SL in the pair in each bias polarity is able to provide photoelectrons to the conduction band of the blocking barrier and affect the barrier conductivity. By designing a different absorption wavelength for each SL in the pair, one can achieve voltage tunable two-color detection. Using this approach, we have demonstrated wavelength switching between 5.8 and 9.5  $\mu\text{m}$  in one sample and 3.9 and 9.2  $\mu\text{m}$  in another.
- a3. QWIP is usually a narrow band detector. Although some broadband detectors exist, they are usually sharply peaked at certain wavelengths. The spectral linewidth is temperature dependent, and a large bias is needed. We have designed a binary superlattice structure to achieve uniform responsivity within 8 -14  $\mu\text{m}$  window with

negligible temperature dependence. These performance characteristics are achieved by judiciously choosing the binary basis of the superlattice with the desirable QW wavefunctions for uniform dipole oscillator strength and wavelength distribution across the spectrum. Fig. 3 shows the band structure of the superlattice unit cell. With this structural design, the calculated spectra for different doping density are shown in Fig. 4. The measured spectral response in Fig. 5 compares well the calculation. The small difference is due to the decreasing tunneling probability of the photoelectrons out of the superlattice.

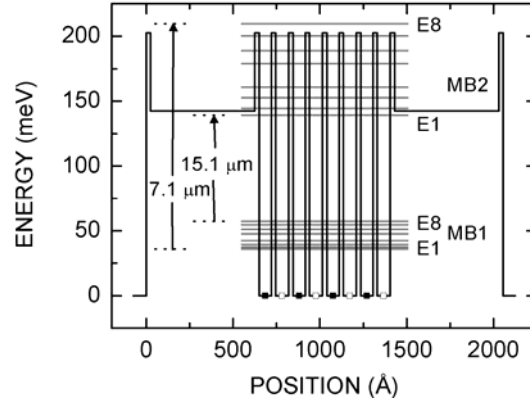


Fig. 3 The band structure of a binary superlattice infrared photodetector.

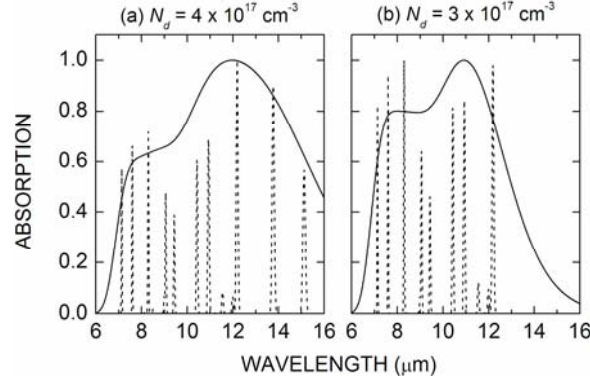


Fig. 4 The calculated absorption spectra for two doping densities.

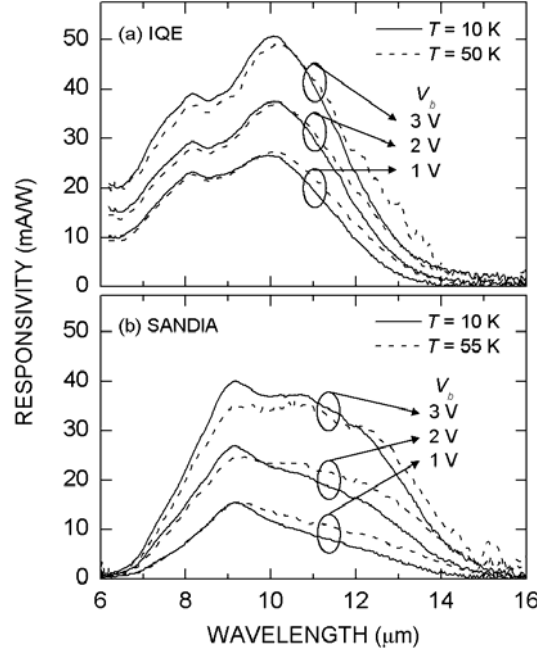


Fig. 5 The measured responsivity for two samples. The sample from IQE matches the calculated response for  $N_d = 3 \times 10^{17} \text{ cm}^{-3}$ . The sample from Sandia Lab matches the calculated response for  $N_d = 4 \times 10^{17} \text{ cm}^{-3}$ .

- a4. Two-color QWIPs and broadband QWIPs are of little value if normal incident radiation cannot be coupled into detector across a wide spectrum. The usual grating is known to be narrow band. We have studied the corrugated light coupling scheme, and demonstrated its effectiveness in these QWIP structures.

b. Nano-patterned quantum-dot QWIP's.

The approach in this work is to create three-dimensionally quantum confined structures. Their energy level spacing due to size quantization is in the infrared regime. In contrast to the usual methods of obtaining quantum dots, which is through material growth techniques, we start with the multiple quantum well structures. These structures create one-dimensional quantum quantization vertical to the material layers, and they are the usual quantum well infrared photodetector (QWIP) material used for infrared imaging. With this material, we start out with a detector system that is sensitive to infrared and exhibits good material quality.

We then create additional size quantization through nano-lithography, first to create nanowires for two-dimensional confinement, and then crossed-grids for three-dimensional confinement. The latter utilizes the fact that when the physical width is less than the charge depletion width at the two sidewalls, the conducting width along the channel will be zero. In such case, only pockets of electrons remain at the intersections of the grids, where there are no sidewalls. three-dimensional confinement is thus created.



The top contacts of these nanostructures are connected through the top metal layer, which remains conducting even down to submicron scale. Fig. 1 shows the different patterns of the detectors fabricated. Fig. 1(a) is a series of quantum dots connected by nanowires. Fig. 1(b) is a series of nanowires. Fig. 1(c) is the crossed grid structure. Fig. 1(d) is the cross-section of the grid.

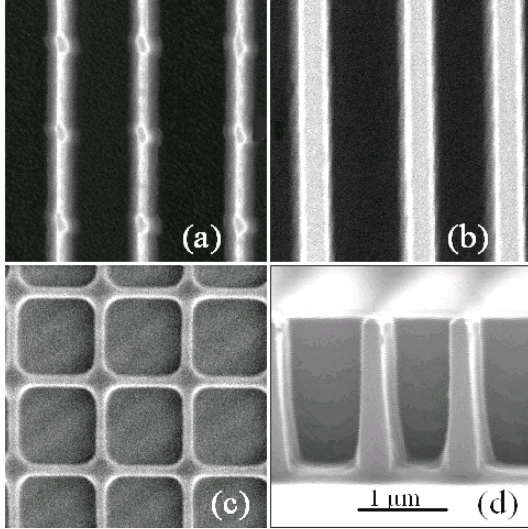


Fig. 1 (a) is the quantum dots, (b) is the quantum wires, (c) is the quantum grid and (d) is the cross-section of the structure in 1(c).

To characterize the quantum wires, we measured the resistance  $R$  of the wires between the top contact and the bottom contact with different physical width  $w_1$ . As expected, the value of  $R$  increases as  $w_1$  decreases. Meanwhile, we also measured the resistivity  $\rho$  of the material from a large area detector. By equating  $R = \rho t / w_e L$ , where  $t$  is the material thickness,  $w_e$  is the “conducting” width and  $L$  is the length of the wires, the value of  $w_e$  can be deduced. The quantity  $w_e$  is the actual region of the wire that is occupied by electrons. The rest of the width is occupied by the depletion region. Thus,  $w_1 = w_e + d$ , where  $d$  is the total depletion width along the two sidewalls.

Fig. 2 shows the relation between  $w_e$  and  $w_1$  for two wafers with different doping densities. Wafer #2 has a 10 times higher doping density than wafer #1, and the depletion region appears to be smaller. Fig. 2(a) shows that when  $w_1 < 0.3 \mu\text{m}$ ,  $w_e$  is reduced to zero, and therefore  $d = 0.3 \mu\text{m}$  for wafer #1. Likewise,  $d = 0.25 \mu\text{m}$  for wafer #2. However, wafer #2 shows nonzero conductivity even when  $w_1 < d$ , i.e. the wires are never completely pinched off, and a very thin layer of electrons remains along the center of the wire. If we assume the same resistivity, the value of  $w_e$  is deduced to be 16 nm for the thinnest lines fabricated, where  $w_1$  is 82 nm. This work thus shows that nanostructures can be obtained using e-beam fabrication techniques because of the existence of the natural depletion layers.

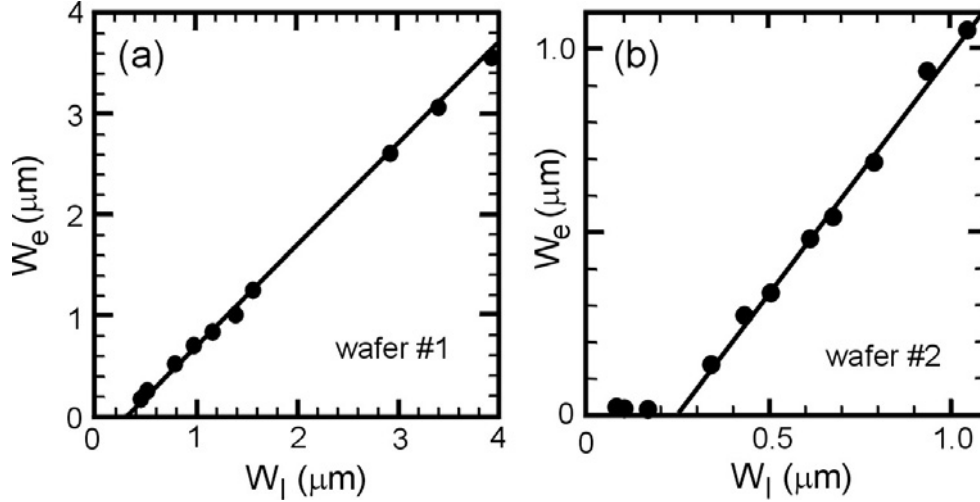


Fig. 2 The relationship between the conducting width  $w_e$  and the physical width  $w_l$  for wafers with (a)  $5\text{E}17\text{ cm}^{-3}$  and (b)  $5\text{E}18\text{ cm}^{-3}$ .

Fig. 3 shows the corresponding infrared responsivity normalized to the same dark current level. The normalization factors out the amount of active materials contained in different widths. The dashed curve connects the data from wafer #1. It has a local maximum at  $w_l = 1.5\text{ }\mu\text{m}$ . As well known, QWIPs do not absorb normally incident light. The peak at  $1.5\text{ }\mu\text{m}$  is due to the resonant scattering effect of the top metal contact on the incoming light. This resonant light coupling effect is confirmed by rigorous EM field modeling.

When  $w_l$  is less than  $1.5\text{ }\mu\text{m}$ , EM modeling predicts a continual reduction of the photoresponse, where it is zero at zero width. Unpredictably, the normalized responsivities, NR, ratio (which is divided by the reponsivity of the edge coupled large QWIP detector) starts to increase when  $w_l$  is less than  $0.5\text{ }\mu\text{m}$ . This could signify the intrinsic infrared absorption in this nanostructure due to horizontal quantization across the wire. To study in detail the possible normal incident absorption, more wires from wafer #2 were made thinner than  $0.5\text{ }\mu\text{m}$ . Fig. 3 shows that when  $w_l$  is less than  $0.5\text{ }\mu\text{m}$ , the response increases as the width decreases. It strongly indicates the quantum size effects.

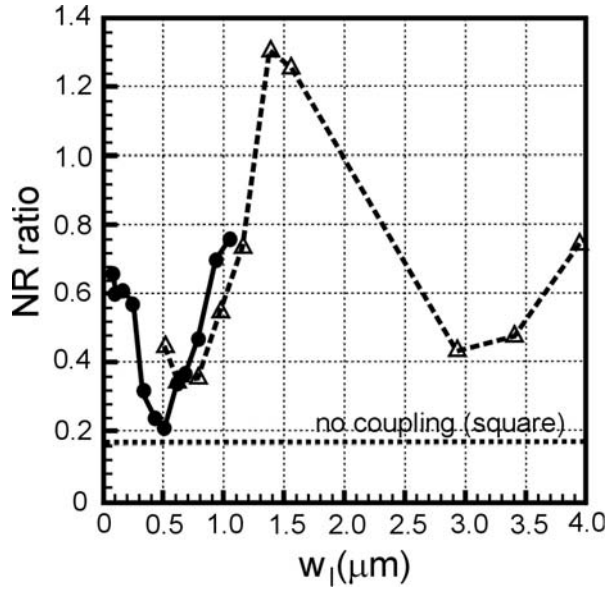


Fig. 3 The photoresponse of the nanowires for different wire width. The dashed curve is for wafer #1 and the solid curve is for wafer #2.

To further support the size quantization, the spectral characteristics need to be investigated. The wire conducting width of  $\sim 16$  nm is wider than the layer thickness of 5 nm. The energy spacing due to horizontal quantization should be smaller than that due to vertical quantization. As a result, the spectrum of the nanowires should be red shifted. In order to make narrower wires, we adopted wet etching instead of dry etching. When wet etching through a metal mask, the material is etched sideways in addition to downward. This creates a thin constriction under the wire mask, where the active layer is located. Fig. 4 and Fig. 5 show the wire cross-sections.

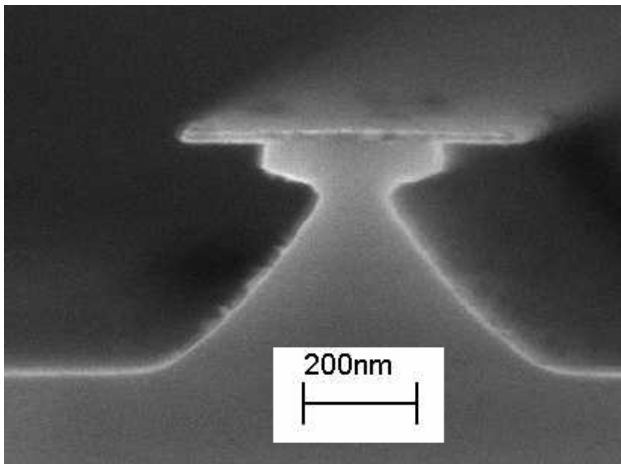


Fig. 4 The quantum wire with  $w_l = 0.12 \mu\text{m}$  at the constriction.

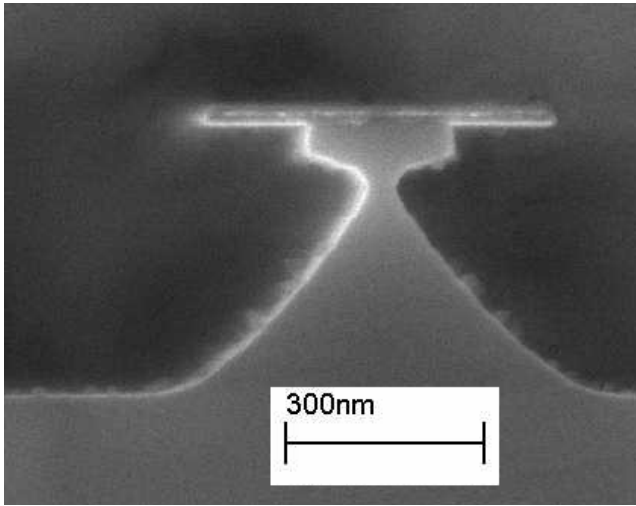


Fig. 5 The quantum wire with  $w_1 = 0.03 \mu\text{m}$  at the constriction.

Fig. 6 shows the spectral responses of wires with different top contact widths from 1.15 to 1.45  $\mu\text{m}$ . The widths of the constrictions were not measured, but were estimated to be  $w_1 \sim 50 \text{ nm}$  and  $w_c \sim 10 \text{ nm}$ . As expected, the wires in general have a longer wavelength response than the monitoring sample, labeled as the null sample. The fact that the wire samples has the same spectral response as the monitoring sample at the shorter wavelengths rules out the effects of inhomogeneous broadening due to material composition fluctuation. Therefore, the observation of the longer cutoff response that is absent in the original QWIP material strongly suggests the creation of new quantum quantization across the wires.

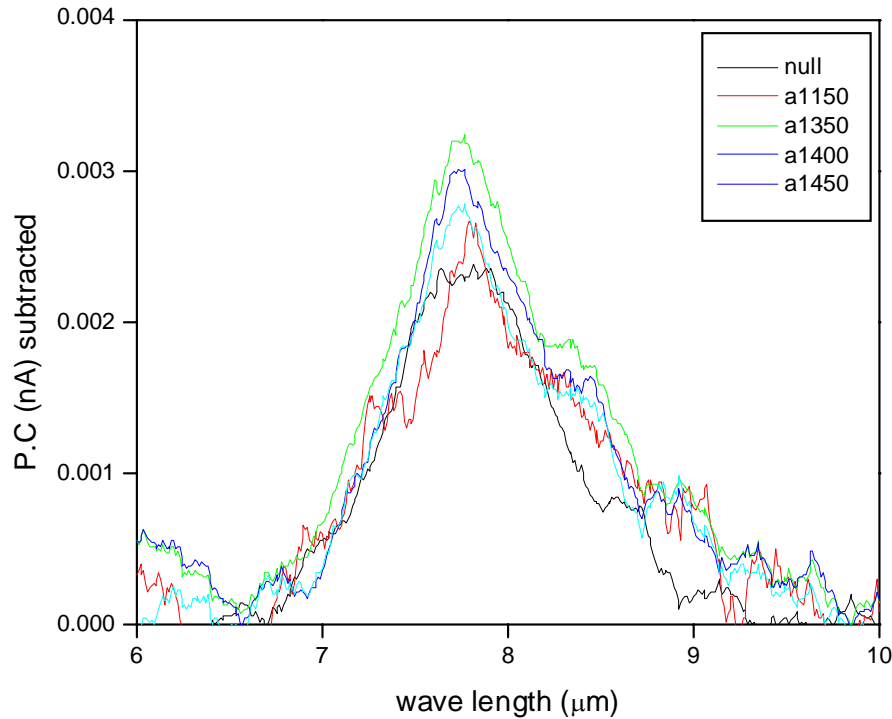


Fig. 6 The broader spectral responses of the nanowires suggest the creation of a new set of energy level spacing by the wire confinement in addition to the original spacing created by the layer confinement.

The investigation of the final three-dimensional confinement of the grids has not been carried out due to the lack of funds.

### III. Publications

#### a. Refereed Journals:

1. "Temperature dependence of electron transfer in coupled quantum wells", Applied Physics Letters, 82, 686 (Feb 2003) A. Majumder, K. K. Choi, J. L. Reno, L. P. Rokhinson and D. C. Tsui.
2. "Broadband and narrow band light coupling for QWIPs" Inf. Phys. & Tech. 44, 309 (Nov 2003), K. K. Choi, C. H. Lin, K. M. Leung, T. Tamir, J. Mao, D. C. Tsui and M. Jhabvala.
3. "Electron transfer based voltage tunable two-color infrared photodetectors", Inf. Phys. & Tech., 44, 337 (Nov 2003), A. Majumder, K. K. Choi, L. P. Rokhinson, J. L. Reno and D. C. Tsui.

4. "Binary superlattice quantum well infrared photodetectors for long wavelength broadband detection", Appl. Phys. Lett., 84, 5127 (Jun 2004), R. Ellis, A. Majumdar, K. K. Choi, J. Reno, and D. C. Tsui.
5. "Voltage tunable two-color infrared detection using semiconductor superlattices", Appl. Phys. Lett., 83, 5130 (Dec. 2003) A. Majumdar, K. K. Choi, J. Reno, and D. C. Tsui.
6. "Voltage tunable superlattice infrared detector for mid- and long-wavelength detection", submitted to IEEE Electron Device Letters, A. Majumdar, K. K. Choi, J. L. Reno and D. C. Tsui.

**b. Presentations and conference proceedings:**

1. "Binary superlattice QWIP for long-wavelength broadband detection", A. R. Ellis, K. K. Choi, D. C. Tsui and J. L. Reno, APS March Meeting, Austin TX March 2003.
2. "Voltage tunable superlattice infrared photodetector for mid- and long-wavelength infrared detection", Amlan Majumdar, K K Choi, J L Reno, and D C Tsui, APS March Meeting, Montreal Canada, 22-26 Mar 2004.
3. "Optimization of corrugated QWIPs for high speed infrared imaging", K. K. Choi, T. Tamir, K. M. Leung, and C. Monroy, F. Wang, and D. C. Tsui, SPIE Defense & Security Symposium, Orlando FL, 12-16 April, 2004.
4. "Designs and Applications of Corrugated QWIPs" (Invited) K. K. Choi, G. Dang, A. Goldberg, C. Monroy, T. Tamir, K. M. Leung, M. Jhabvala, A. La, A. Majumdar, and D. C. Tsui, 2004 Meeting of the Military Sensing Symposia on Detectors, Tucson AZ, 22-26 March, 2004.
5. "Quantum well infrared photodetector technology" (Invited) K. K. Choi, G. Dang, A. C. Goldberg, C. Monroy, T. Tamir, K. M. Leung, M. Jhabvala, A. La, A. Majumdar, D. C. Tsui, IEEE Elect. Dev. & Solid State Circuit Soc., Baltimore Chapter, Historical Electronics Museum, Baltimore, 18 May, 2004.

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